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OPERATIONAL CONSIDERATIONS RELATED TO COCKPIT AUTOMATION AND CREW COMPLEMENT IN THE C-17

by

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Preface

This project comes as the result of many years of flying and watching others fly both high performance and transport aircraft. It is based upon intimate knowledge of both the potential for human error and the saving grace associated with multiple perspectives. It also fully acknowledges and welcomes the vast capabilities associated with increasing levels of automation in aircraft cockpits. Pilots continually play the game of "what if", envisioning possible futures and situations and planning resolutions, given the resources available. Operational decision-makers must continually do the same based upon a realistic understanding of possible mission scenarios and the capabilities and limitations of the aircraft and crew that will fly them.

Abstract

The newest airlifter in the Air Force inventory, the C-17, has a cockpit crew complement of two (pilot and copilot). This is a departure from the traditional airlift crew makeup that included additional crewmembers to handle navigation and aircraft systems. The extensive use of cockpit automation allowed this crew reduction. Major airlines, also making extensive use of cockpit automation, are finding challenges with automation in their fairly routine and mundane ops (compared with that of the military). Recent research has shown that automation can actually, rather than decreasing workload, increase cockpit workload beyond that of less automated aircraft during those periods where workload is already traditionally high. The mission of the C-17 is likely to see a less experienced crew flying low-level in a threat environment, talking to multiple controlling agencies, and trying to get into a location they've never seen after a 15 hour double air-refueling flight from the continental United States. These issues warrant operational consideration when employing the C-17 on some of it’s most demanding missions, and are also applicable to other new or upgraded aircraft where similar cockpit/crew situations exist.

Part 1

To Err Is Human

> *At 2142 eastern standard time (est), on December 20, 1995, American Airlines Flight 965 (AA965), a Boeing 757-223, N651AA, on a regularly scheduled passenger flight from Miami International Airport, Florida, U.S.A., to Alfonso Bonilla Aragon International Airport, in Cali, Colombia, operating under instrument flight rules (IFR), crashed into mountainous terrain during a descent from cruise altitude in visual meteorological conditions (VMC). The accident site was near the town of Buga, 33 miles northeast of the Cali VOR. The airplane impacted at about 8,900 feet mean sea level (msl), near the summit of El Deluvio and approximately 10 miles east of Airway W3. Of the 155 passengers, 2 flightcrew members, and 6 cabincrew members on board, 4 passengers survived the accident. There was no evidence of failures or malfunctions in the airplane, its components, or its systems. Weather was not a factor in this accident.*
>
> — AA965 - Cali Accident Report

Without a doubt, the only certainty associated with human performance is error. The degree to which this inherent error influences the desired outcome determines the relative success of the endeavor. Since the concept of error is central to the discussion to follow, it should be defined as it applies to aviation. For the purposes of this paper, I will define error as; “the action or inaction that leads to a deviation from crew or organizational intentions or expectations.”[1]

A Quick Look Back to Cali

The captain of AA965 had flown into Cali thirteen times without incident. Both of AA965's pilots were experienced in the airplane and proficient in the use of it's automated systems, as noted by their peers.[2]

The B-757 is a modern, highly automated aircraft that uses a Flight Management System (FMS) and integrated flight management computer (FMC). This is the "heart" of the automated cockpit and contains a worldwide navigation data base and performance data which, combined with pilot inputs, govern autothrottle and autopilot functions. The FMS monitors the system and engine status and displays the information, as well as airplane attitude, flightpath, navigation, and other information, through cathode ray tube (CRT) displays. Pilot inputs into the FMS can be performed either through a keyboard and associated CRT, or to a more limited extent via controls on the glareshield

On December 20, 1995, most likely because of the self-induced time pressure and an attempt to execute the approach without adequate preparation, the crew of AA965 committed a critical error by executing a change of course through the FMS without verifying its effect on the flightpath. The evidence indicates that either the captain or the first officer selected and executed a direct course to the identifier "R," in the mistaken belief that R was Rozo (the intended fix) as it was identified on the approach chart. The pilots could not know without verification with the cockpit navigation displays or considerable calculation that instead of selecting Rozo, they had selected the Romeo beacon, located near Bogota, some 132 miles east-northeast of Cali. In executing a turn toward Romeo rather than Rozo, the crew had the airplane turn away from Cali and towards mountainous terrain to the east of the approach course, while the descent

continued. At this time, both pilots also attempted to determine the airplane's position in relation to the initial approach fix (IAF). Neither pilot was able to determine why the navaid was not where they believed it should be, and neither noted nor commented on the continued descent. The cockpit voice recorder (CVR) indicates that the flightcrew became confused and attempted to determine their position through the FMS. For example, at 2138:49 the first officer asked, "Uh, where are we?" and again, 9 seconds later asked, "Where [are] we headed?" The captain responded, "I don't know ... what happened here?" The discussion continued as each attempted to determine the position and path of the airplane relative to the approach to Cali. Less than three minutes later, the aircraft impacted the ground.

The probable causes listed in the investigation are:

1. The flightcrew's failure to adequately plan and execute the approach to runway 19 at Cali and their inadequate use of automation.
2. Failure of the flightcrew to discontinue the approach into Cali, despite numerous cues alerting them of the inadvisability of continuing the approach.
3. The lack of situational awareness of the flightcrew regarding vertical navigation, proximity to terrain, and the relative location of critical radio aids.
4. Failure of the flightcrew to revert to basic radio navigation at the time when the FMS-assisted navigation became confusing and demanded an excessive workload in a critical phase of the flight.

This accident was not caused by the automated systems on AA965. Many opportunities existed for a break in the chain of events that led to their controlled flight into terrain. There were, however, automation issues that played a significant role in the decision making that took place that night with that crew.

Notes

[1] Robert L. Helmreich, James R. Klinect, & John A. Wilhelm, *Models of Threat, Error, and CRM in Flight Operations*, (Presented at the 10th International Symposium on Aviation Psychology Columbus, Ohio: May 3-6, 1999).

[2] *Aircraft Accident Report. American Airlines Flight 965. Boeing 757-223, N651AA. Near Cali, Colombia*, Aeronautica Civil Of The Republic of Colombia, 20 Dec 1995.

Part 2

Setting The Stage

Real knowledge is to know the extent of one's ignorance.

— Confucius

Automation Issues – A Short Primer

In the early 1980s, the aviation industry began to embrace the new capabilities made possible with the growth in computer technology. Automated systems and computers began to take the place of traditional systems. As the automated systems and levels of information available to pilots grew, accidents and incidents related to the new systems also grew, as would be expected. The increased automation also made possible smaller crew sizes because of the ability to automate the systems traditionally monitored and controlled by dedicated navigators and flight engineers. This is the environment in which the United States Air Force (USAF) and the prime contractor McDonnell Douglas designed and built the C-17.

C-17 Automation Philosophy

With the capabilities now available because of automation, the C-17 was designed to operate with a cockpit crew of only two pilots. The crew of the aircraft it was designed to replace, the C-141, had included as part of the crew both a navigator and flight

engineer. Although borrowing heavily from the equipment in the automated cockpits of its civilian transport counterparts, some basic cockpit design philosophies were significantly different with C-17. Bill Casey, Chief Pilot for McDonnell Douglas, described the differences as "instead of automated high technology, like the commercial world, we used the Lincoln Logs, or a simplified, "dumb" cockpit approach. If you don't know what it does, don't touch it, and it won't do anything."[1] This philosophy was designed to allow for the lower experience level and more demanding missions of the average military pilot, compared to his/her civilian counterpart. A tradeoff in this decision is that "an expert in the C-17 cockpit will have to push more buttons to command a specific action than his airline counterpart."[2]

The automation philosophy outlined in the directive that governs flight operations for the C-17 supports this by saying pilots should use appropriate levels of automation as required by the flight conditions - their first priority is to fly the aircraft. It goes on to say that "The Automatic Flight Control System (AFCS) and Mission Computer (MC) are intended to aid in workload management, not complicate it. As the flight situation changes, [pilots should] not feel locked into a level of automation."[3]

Major Automation Issues

Under a grant from the US Federal Aviation Administration, a team of researchers from Oregon State University and Research Integrations, Incorporated recently conducted a study on human factors issues of commercial transport aircraft flight deck automation that drew from many sources.[4] This study surveyed aviation experts, reviewed literature and accident reports, and analyzed incident reports to compile data and other objective evidence related to flight deck automation issues. In the study, they compiled a list of

flight deck automation human factors issues and related evidence. They rank ordered these issues in several ways based upon data found during surveys, literature reviews, and incident and accident analysis. Based upon the multiple rankings and criteria across the span of data collected, they also developed a meta-ranking of the issues.[5] The top five issues (from Table 3, Appendix A) related to flight deck automation in this meta-ranking were:

1. Automation may demand attention.
2. Automation behavior may be unexpected and unexplained.
3. Pilots may be overconfident in automation.
4. Failure assessment may be difficult.
5. Behavior of automation may not be apparent.

Monitoring and Workload

Associated with cockpit automation and error is the concept of monitoring. Automated systems must be continually monitored to ensure safe operation. Independent studies by both the International Civil Aviation Organization (ICAO) and the National Transportation Safety Board (NTSB) show that inadequate monitoring has contributed to a large number of the accidents.[6]

Another related issue is that of workload. Automated systems are designed to decrease workload through automation of control, navigation and information systems. Studies are now indicating however, that automation may not always work as designed. During periods where workload is traditionally low, such as during cruise, workload is decreased and pilots simply monitor the systems. During periods of traditionally high workload, however, automation can actually *increase* crew activity, such as during departures and arrivals.[7] Even small increases in workload during these time-critical phases of flight can have serious implications.

Who Gets the Job Done?

There are some important points to address here. Certain levels of automated systems must be used to operate and navigate modern aircraft. The roles and responsibilities of the crew positions that were eliminated (in the case of the C-17, the navigator and flight engineer) must still be accomplished, either through the use of on-board automated systems or manually by the pilots. Reversion to manual flight and navigation in lieu of using the AFCS and MC adds further to the workload in the cockpit, although it may decrease the cognitive issues associated with trying to cope with an automated system which is not fully understood or is functioning in a confusing way.

Crew Resource Management (CRM) and It's Role

In the early 1980s, programs were started with the intent of reducing accidents that came as a result of pilot error. The training programs focused on group dynamics and awareness. Scenarios were used to examine how situations can develop in which it is possible to "break the chain" of events that could culminate in a compromise in safety through leadership, group skills, and communication. CRM has been developed and refined over the years but continues to be a very important part of the training that Air Force and civil aircrew receive. Today, strategies and techniques for dealing with automation are central issues in CRM training. Mission oriented simulator training and regular simulator and in-flight training using varying degrees of automation ensure familiarity with automated systems, proficiency in dealing with simulated emergencies, and continued honing of manual skills. CRM is the primary line of defense against the threats to safety that are present in aviation and inherent in human performance.

The Threat and Error Management Model

It is important to understand that cockpit automation can impact the workload on the flight deck, and ultimately the potential safety of the crew. Even more important from an operator and operating organization standpoint is trying to understand how this impact occurs, and how best to deal with it. One model recently introduced by researchers at the University of Texas at Austin is the Threat and Error Management Model (TEMM). Through extensive participation in Line Operations Safety Audits (LOSA) of carriers, the group developed a general model of threat and error in aviation. Beginning with both external and internal sources of threat and applying CRM behaviors to recognize and avoid or detect and manage, several outcomes are possible.[8] Figure 1 is a graphic depiction of this basic model.

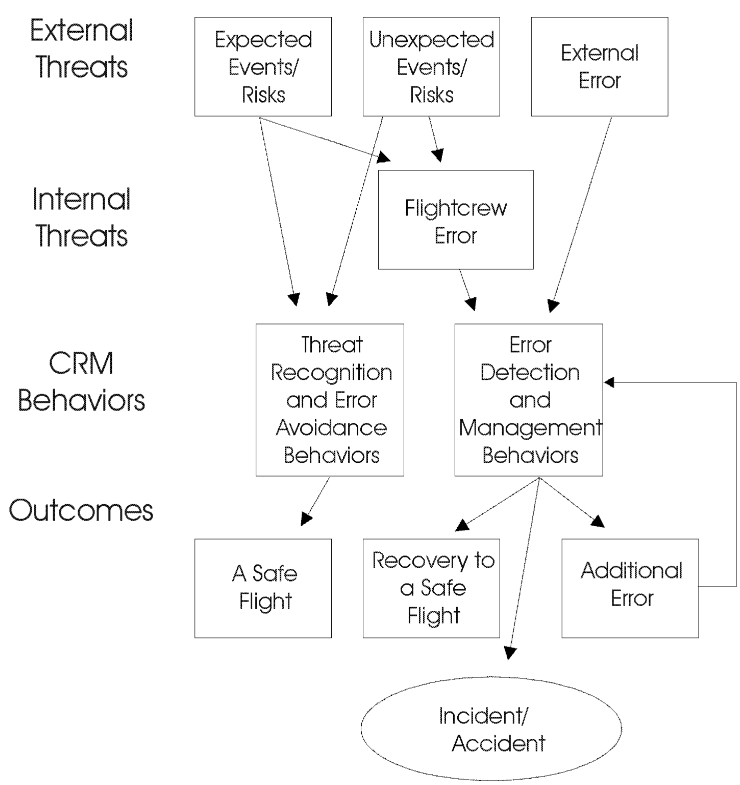

Figure 1 The Model of Flightcrew Error Management [9]

Using this model, a structure exists that can be used to examine a particular incident or a notional mission. In this case, it will be used to frame the mission issues that a C-17 crew is likely to encounter.

C-17 Mission Description

The C-17 Aircraft

As described in the Flight Manual: *The C-17 is a long-range, air-refuelable, heavy logistic transport aircraft. It's design characteristics give it the capability to operate into and out of short runways and austere airfields carrying large payloads. The engine thrust reverser system is capable of backing a fully loaded aircraft. The pilots are provided with Head Up Displays (HUD), four Multi-Function Displays (MFD) and redundant mission computers which reduce pilot workload and enhance mission capability. Station Keeping Equipment (SKE) is provided for multiship formation flights and airdrop in instrument meteorological conditions (IMC). This widebody aircraft is designed to airlift palletized cargo, rolling stock, troops, passengers, and aeromedical evacuation patients. An aerial delivery system provides the capability to airdrop troops or a variety of materiel and equipment systems.*[10]

The Mission

The mission capabilities of the C-17 are significantly different from modern civilian transports. For the purposes of this paper, I will describe the mission tasks rather than look at a particular mission.

A final consideration related to the mission of the C-17 is that of flight duty periods. Flight duty period, according to AFI 11-202, Volume 3, is the period that starts when an

aircrew reports for a mission, briefing, or other official duty and ends when engines are shut down at the end of a mission.[11] The standard flight duty period for a two-pilot crew in the C-17 is 16 hours. During contingency operations, it is not uncommon to have this standard flight duty period extended by an hour or two based upon the nature of the operation.[12] With an additional pilot, a crew may be considered "augmented" and have their allowable flight duty period extended to 24 hours.[13]

Notes

[1] Bruce D. Nordwall, "Military Cockpits Keep Autopilot Interface Simple", *Aviation Week and Space Technology,* 6 February 1995, 54.

[2] Ibid., 54.

[3] AFI 11-2C-17, vol 3, *C-17 Operations Procedures,* para 5.30.2.

[4] Ken Funk, Beth Lyall, and Candy Suroteguh. *Flight Deck Automation Issues*, on-line, Internet, 22 March 2000, available from http://flightdeck.ie.orst.edu/FDAI/issues.html

[5] Ken Funk, Beth Lyall, and Candy Suroteguh. *Flight Deck Automation Issues*. *Issues Ranked by Multiple Criteria (Meta-Ranking);* on-line, Internet, 22 March 2000, available from http://flightdeck.ie.orst.edu/FDAI/Meta-Analysis/meta(bu_Meta_Ranking).html.

[6] "What ASRS Data Tell About Adequate Flight Crew Monitoring", *NASA Callback,* No. 219, (Sep 1997).

[7] David Hughes and Michael A Dornheim, "Accidents Direct Focus on Cockpit Automation", *Aviation Week and Space Technology*, 30 January 1995, 52.

[8] Robert L. Helmreich, James R. Klinect, & John A. Wilhelm, *Models of Threat, Error, and CRM in Flight Operations*, (Presented at the 10th International Symposium on Aviation Psychology Columbus, Ohio: May 3-6, 1999).

[9] Ibid.

[10] T.O. 1C-17A, 1-15.

[11] AFI 11-202, vol 3, *General Flight Rules*., 43.

[12] AMCPAM 10-210, *Stage Crew Management,* 9.

[13] AFI 11-202, vol 3, *General Flight Rules*, 44.

Part 3

C-17 Mission Analysis Using the TEMM Model

You may have to fight a battle more than once to win it.

— Margaret Thatcher

The external and internal threats identified in the following sections are simply some of those suggested by experience and recent research. The identified items in no way comprise a comprehensive list, but they do provide a good basis to frame a discussion of some of the issues at hand.

External Threats

Table 1 Potential External Threats In C-17 Mission

Expected Events/Risks	Unexpected Events/Risks
Terrain/Low-Level Flight	Mission Change
Language Barriers	Mechanical Problems
Procedural Change	Missed Communications
Multiple Controlling Agencies	Unexpected Air Traffic
Formation Flight	Controlling Agency Error
Surface-to-Air/Air-to-Air Threats	Unexpected Weather
	Poor/Incorrect Intelligence Information
	Pressure to Accomplish Mission

External threats are those situations, events, or errors that originate from outside the cockpit.[1] They are inherent in both military and civilian flying, and have been since aviation began. Unique challenges exist for the military pilots because of the nature of

the environments in which they fly. Table 1 gives examples of some of the expected and unexpected risks that could be encountered on an operational C-17 mission. Expected risks may be thought of as those routine risks that are not outside the expectations for a routine mission, while unexpected risks are those outside the bounds of the “normal mission.” Training scenarios and mission oriented simulators incorporate a variety of these same threats in order to practice procedures and review tactics and techniques for dealing with any one or a combination of such external threats. Automated systems, such as the aircraft defensive systems, are also present that aid in detection and resolution of some of the threats.

Internal Threats

Unlike the external threats, I will focus on several specific internal threats because they are inherent (to some extent) in any crew, and typically exacerbate the effect of external threats.

Table 2 Potential Internal Threats In C-17 Mission

Internal Threats
Unfamiliarity With Location/Destination
Fatigue/Mission Duration
Challenging Flight Maneuvers
Crew Inexperience
Intentional Noncompliance
Automation Interface Issues

Unfamiliarity With Location/Destination

Unfamiliarity with an area or destination is not an unusual aspect of an operational airlift or airdrop mission. In fact it is entirely possible that prior to a mission, a pilot will

not have heard of the destination *country*, let alone the destination *airfield*. In 1997, air mobility forces transited all but five of the world's countries, three of which had no airfield.[2]

Air Mobility Command (AMC), the controlling major command for the USAF mobility forces, strives to provide airfield information to aircrews. All airfields that are likely to be transited by USAF aircraft have been surveyed for suitability. This database is maintained in the form of an Airfield Suitability and Restrictions Report (ASRR), which contains specific runway and taxiway information on an airfield, along with restrictions such as daylight operations only. Some more routinely transited airfields have videotapes on file that visually take the viewer down an approach to the various runways at the field, and discuss terrain and airfield hazards. Airfields that are considered particularly hazardous are often designated as certification airfields, meaning that before flying into that airfield/region in command of a mission, the pilot must have flown there with another pilot familiar with the area.

Fatigue/Mission Duration

Fatigue has significant implications concerning error. The crew duty periods regularly encountered by mobility aircrew can create challenges due to fatigue. A NASA Technical Memorandum (TM) on the issue of civilian airline crew duty periods indicated that scientific findings from a variety of sources, including data from aviation, demonstrate a significantly increased vulnerability for performance-impairing fatigue after 12-hours.[3] Another aspect of this issue is *when* missions are flown. From personal experience, we know that performance drops during the normal nighttime sleep period and that it is more difficult to sleep during the day. Research has often confirmed these

commonly known facts as they relate to aviation. A NASA TM concludes that "circadian disruption can lead to acute sleep deficits, cumulative sleep loss, decreases in performance and alertness, and various health problems." A study of naval watch keepers found that between 0400 to 0600, response rates drop 33 percent, and response speed eight percent, compared with rates between 2000 to 2200 hours.[4]

The NASA memorandum recommends that flights and missions take "circadian stability" into account. NASA goes on to state that nighttime flying imposes different physiological challenges as compared to daytime flying. These differences must be accommodated in the timing and duration of rest periods and would also require limiting the number of consecutive nights of flying.[5]

Challenging Flight Maneuvers

The nature of military flying and the unpredictable and sometimes hostile environment which they train for and fly in often requires challenging flight maneuvers designed to limit exposure to other external threats. Some of these maneuvers include formation flight with multiple aircraft occupying a relatively small airspace, extended low-level flight requiring constant maneuvering both to avoid terrain and use it for threat avoidance, specially designed threat avoidance approach and departure procedures which involve greater maneuvering and climb/descent rates than normally used, and landings/takeoffs on short/austere unimproved runways. The C-17 is designed to be capable of flight maneuvers which allow it to operate in this environment. These capabilities increase workload and themselves may become threat sources. Commercial flying has fewer of these threat sources, but a statistical summary of accidents for the worldwide commercial jet fleet between 1988 thru 1997 indicate that the flight

maneuvers associated with takeoff, initial climb, final approach, and landing account for 68 percent of the accidents, while only constituting 6 percent of the flight time.[6] These flight segments are typically involve both vertical and horizontal maneuvering near terrain. The autopilot is typically off for a portion of this flight segment, but interaction with automated systems for navigation, aircraft configuration and situational awareness is at a peak level. It is also the period where modes are being changed to and from automated flight. It is within these flight segments where cockpit workload is the highest, and where the need to monitor and interact with automated systems may further increase workload as discussed earlier.

Crew Inexperience

The experience of military pilots varies widely, but compared to their civilian counterparts at the major airlines, the military pilots are relatively inexperienced. Military airlift pilots typically upgrade to aircraft commanders when they meet the minimum number of flying hours required. For the C-17, this can be as low as 1300 hours (total USAF flying and simulator time – not all in the C-17).[7] 200 hours later, the pilot may upgrade to the instructor pilot position. In contrast, to be hired as a copilot by Southwest Airlines requires a minimum of 2500 hours total or 1500 hours in a turbine aircraft to including a minimum of 1000 hours in turbine aircraft as the Pilot in Command (specifically excludes any simulator time).[8] The total number of flight hours logged by the military pilot do not alone pose a threat; however, experience and "airmanship" are still being developed (due to the lower experience level) to a much greater degree. This lower experience level can result in steeper learning curves, fewer "real life" experiences to draw on, and less maturity. The military counters this with a much more robust and

comprehensive training program than is provided to the civilian airline pilots. This cannot however, fully substitute for real-world experience.

Intentional Noncompliance

A recent University of Texas study found after observing 184 commercial flight crews during Line Operations Safety Audits that the most frequently committed (and also least consequential) errors by the crews were intentional noncompliance.[9] These include willful violations of established procedures, such as failure to reference checklists. Anecdotal evidence also suggests that the tendency to deviate from procedure and skip standard operating procedure (such as checklist usage) increases during periods of high workload where time and excess capacity become limited.

Automation Interface Issues

The previous internal threats addressed have been inherent in military flying for many years. Part two outlined several automation issues associated with modern aircraft. Through the use of automation, the USAF has decreased the minimum cockpit crew size to two pilots in the case of the C-17. Cockpit automation offers significant benefits and capabilities; however, it also brings with it human factors issues and potential threats that are very real. The scope and implications of these threats are still being studied, and are far from being fully understood. When faced with an emergency, USAF pilots are taught from the very start of their careers to do four things:

1. Maintain Aircraft Control
2. Analyze the situation
3. Take Appropriate Actions
4. Land as Soon as Conditions Permit

This process is now inextricably linked with computer systems and automation. In 1988, McDonnell Douglas conducted an aircrew workload evaluation using a full mission scenario (as envisioned at the time). One of the purposes of this initial evaluation was to establish confidence that aircrew workload was within acceptable limits during ideal mission conditions (no unexpected external threats).[10] This evaluation found no periods during which workload was classified as *very high* or greater; however, long periods (30 minutes during low altitude cruise) were found in which the workload allowed *very little spare capacity, but maintenance of effort in the primary tasks not in question*.[11] This lack of spare capacity in the automated two person cockpit, coupled with the addition of unexpected external threats and some of the automation issues described in Part 2 may be significant.

Where It Comes Together

As shown in the TEMM model, the front line for recognizing and avoiding or detecting and managing threats is the crew. The model describes this as CRM behaviors, but it comes down to people. Operationally, the C-17 is required to have a minimum crew of two pilots. Missions are frequently flown with additional pilots due to crew ratio (number of crew to number of available aircraft) and training requirements. A third pilot can drastically decrease the workload on a crew by performing basic tasks and acting as an observer. As an observer, they can often maintain a greater sense of situational awareness, and provide input as needed to increase the capacity of the crew as a whole. During periods of high workload, a third pilot is an extra set of eyes and ears that can take on more tasks to decrease the load on the pilots that occupy the primary crew positions. When missions are frequently flown with additional pilots, negative training

can occur as the crews naturally become accustomed to delegating tasks and having an extra hand available during periods of high workload. The impact of this can be a crew unaccustomed to working without an extra hand if operational requirements push crew size back to the basic two-pilot crew.

We have discussed how individuals are sources of error, but they are also the last defense against an error leading to an incident or accident. Their effective use of CRM in managing all of the resources at their disposal to safely accomplish a mission is the desired goal.

Notes

[1] James R. Klinect, John A. Wilhelm, and Robert L. Helmreich, *Threat and Error Management: Data From Line Operational Safety Audits*, (Austin, TX: The University of Texas Team Research Project. 1999), 1.

[2] Keith Hutcheson, *Air Mobility – The Evolution of Global Reach*, (Vienna, VA: Point[One]VII, 1999), Attached Slide Presentation.

[3] Dinges, D. F., Graeber, R. C., et al. *Principles and Guidelines for Duty and Rest Scheduling in Commercial Aviation,* NASA Technical Memorandum 110404, (Moffett Field, CA: NASA Ames Research Center, May 1996), para 1.1.1.

[4] Smiley, A. *Interpretation of Operator Performance Data*. In: Operator Performance Measurement: Developing Commonality Across Transportation Modes - Proceedings of a September 1994 Workshop. DOT Human Factors Coordinating Committee Final Report, (Nov 1996).

[5] NASA, *Crew Factors in Flight Operations VII: Psychophysiological Responses to Overnight Cargo Operations*. NASA Technical Memorandum. (Dec 1995), 40-41.

[6] Boeing Commercial Airplane Group, *Statistical Summary of Commercial Jet Aircraft Accidents: Worldwide Operations, 1959-1997*. (Seattle, WA; Published annually by Airplane Safety Engineering, 1998), 20.

[7] AFI 11-2C-17, vol 1, *C-17 Aircrew Training*, 33.

[8] Southwest Airlines, *Southwest Airlines New Pilot Requirements: Flying Experience*; on-line, Internet, 22 March 2000, available from http://www.iflyswa.com/careers/pilots.html.

[9] James R. Klinect, John A. Wilhelm, and Robert L. Helmreich, *Threat and Error Management: Data From Line Operational Safety Audits*, (Austin, TX: The University of Texas Team Research Project. 1999), 6.

[10] McDonnell Douglas Corporation, *C-17 Aircrew Workload Evaluation* Report MDC J9289 Revision B (28 Oct 1988), 4.

[11] Ibid., 29.

Part 4

Conclusions

You live and learn. Or you don't live long.

— Lazarus Long[1]

The TEMM model (figure 1) depicted earlier provides a good structure with which to view the operational hazards associated with mobility operations in the C-17, the demands on and sources of error within a crew, and the ultimate responsibility levied on pilots.

Error is inherent in everything that we do. In aviation, technical proficiency, established organizational procedures, the ability to maximize the benefits of working as a crew, and the ability to work as a crew to recognize and mitigate both internal and external errors are key to safe and effective mission accomplishment. Realistic training with an emphasis on crew coordination and use of automation can greatly improve effectiveness and safety. It is the responsibility of operational organizations to conduct planning and training with an understanding of this.

Military transport and tanker aircraft operate on a routine basis with generally less experienced aircrews and flying more demanding mission than their civilian counterparts. At the extreme, they operate in a hostile environment. Automated systems can and have vastly increase the capability of military transport and tanker aircraft, but studies are also showing that cockpit automation can also negatively affect the performance *during the*

times when it can least be afforded. In the case of the C-17 the cockpit is designed in such a way that maximum use of automation is more demanding than that of large civil aircraft. Presumably, this may also apply in the case of other military aircraft that are being planned, built, or upgraded using highly automated systems.

Initial workload evaluations conducted to validate the crew complement indicated that portions of the envisioned mission, specifically the descent, low altitude cruise, and approach/landing, had workloads that allowed very little spare capacity. Many modifications have been made to C-17 aircraft systems from those for which that evaluation was conducted, but during that time we have also learned more about the potential for automation to add to workload.

Addition of a third crewmember creates a significant synergistic effect in the ability of a crew to deal with mission demands. The routine (but informal) addition of a third crewmember with no formal plan to ensure their presence during demanding missions could result in a crew that is less prepared to operate under those critical conditions. Addition of a third crewmember significantly bolsters the last line of defense against both internal and external threats, and can greatly enhance the safety and capability of a crew to deal with an uncertain environment. With these considerations in mind, a formal evaluation of the potential benefits of a three-person cockpit for those missions that are the most demanding may be warranted. In any event, leaders making operational decisions related to employment of the C-17 must be aware of the issues associated with modern, highly automated aircraft, as well as the crew limitations and potential for human error that have been part of aviation since its earliest days.

Notes

[1] Robert A. Heinlein, *The Notebooks of Lazarus Long* (Rohnert Park, CA: Pomegranate Artbooks, 1995).

Appendix A

Flight Deck Automation Issues

Table 3 Top 20 Flight Deck Automation Issues (Multiple Criteria) [1]

Meta Ranking	Abbreviated Issue Statement (Study Issue ID)	Ranking (Out of 92)				Sum of Rankings
		By Citation	By Expert Agreement	By Expert Criticality	By Sum of Strengths	
1	Automation May Demand Attention (102)	1	2	10	18	31
2	Automation Behavior May Be Unexpected And Unexplained (108)	3	23	18	8	52
3	Pilots May Be Overconfident In Automation (131)	2	32	23	5	62
4	Failure Assessment May Be Difficult (025)	16	6	17	26	65
5	Behavior Of Automation May Not Be Apparent (083)	7	20	34	6	67
6	Mode Transitions May Be Uncommanded (044)	25	4	11	31	71
7	Mode Awareness May Be Lacking (095)	11	54	3	10	78
8	Mode Selection May Be Incorrect (145)	33	21	13	16	83
9	Situation Awareness May Be Reduced (114)	17	50	6	12	85
10	Understanding Of Automation May Be Inadequate (105)	4	57	35	1	97
11	Human-Centered Design Philosophy May Be Lacking (100)	32	15	12	39	98
12	Training May Be Inadequate (133)	5	46	45	3	99
13	Crew Assignment May Be Inappropriate (142)	49	33	20	30	102
14	Automation May Not Work Well Under Unusual Conditions (150)	28	47	28	15	104
15	Pilots May Over-Rely On Automation (106)	15	62	39	4	105
16	Pilots May Be Out Of The Loop (002)	18	8	5	22	107
17	Database May Be Erroneous Or Incomplete (110)	30	37	44	32	114
18	Manual Skills May Be Lost (065)	6	61	64	9	116
19	Automation May Be Too Complex (040)	13	51	37	11	122
20	Interface May Be Poorly Designed (039)	10	11	49	13	123

Notes

[1] Ken Funk, Beth Lyall, and Candy Suroteguh. *Flight Deck Automation Issues. Issues Ranked by Multiple Criteria (Meta-Ranking);* on-line, Internet, 22 March 2000, available from http://flightdeck.ie.orst.edu/FDAI/Meta-Analysis/meta(by_Meta_Ranking).html.

Appendix B

Accidents/Fatalities by Phase of Flight

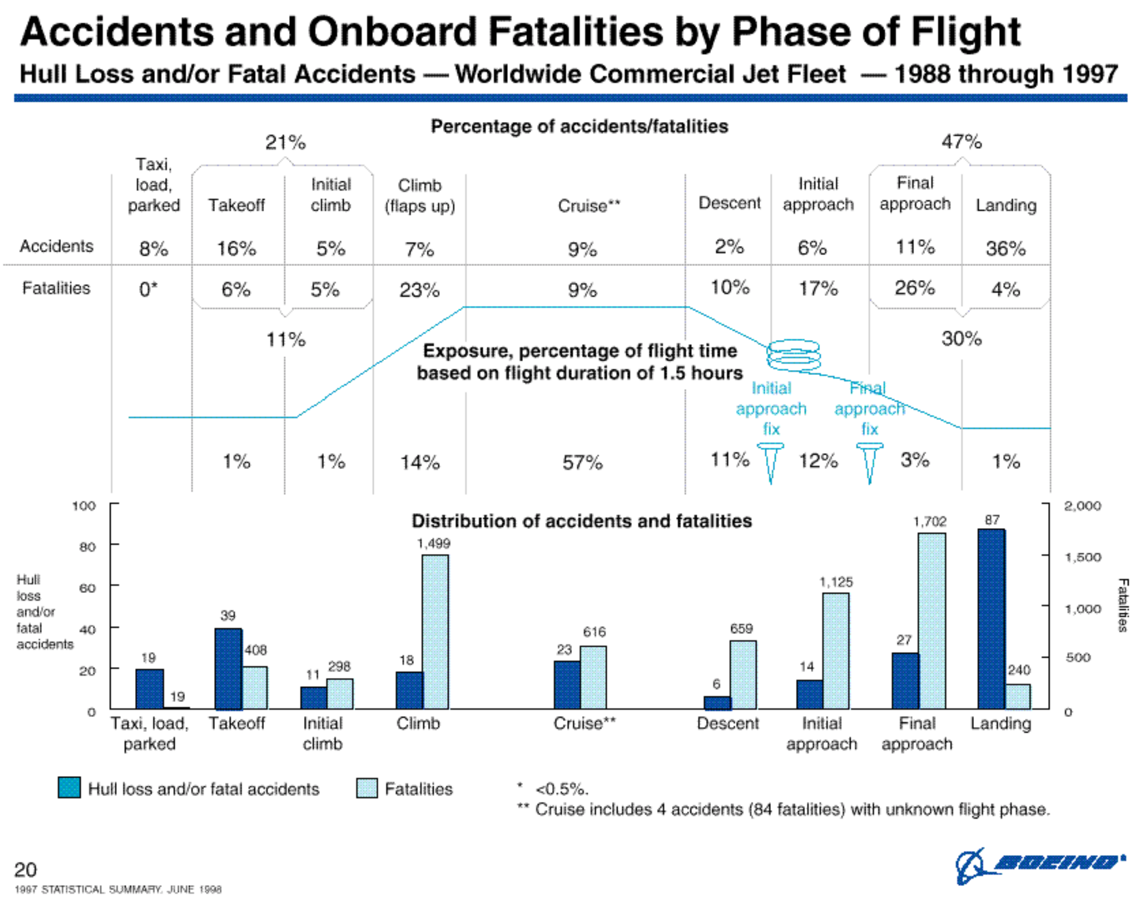

Figure 2. Accidents/Fatalities By Phase of Flight 1988-1997[1]

Notes

[1] Boeing Commercial Airplane Group (1998). *Statistical Summary of Commercial Jet Aircraft Accidents: Worldwide Operations*, 1959-1997. Published annually by Airplane Safety Engineering, pg. 20.

Glossary

AFCS	Automatic Flight Control System
AMC	Air Mobility Command
ASRS	Aviation Safety Reporting System
CRM	Cockpit/Crew Resource Management
CRT	Cathode Ray Tube
CVR	Cockpit Voice Recorded
FMC	Flight Management Computer
FMS	Flight Management System
HUD	Heads Up Display
ICAO	International Civil Aviation Organization
IMC	Instrument Meteorological Conditions
IFR	Instrument Flight Rules
LOSA	Line Operational Safety Audit
MC	Mission Computer
MFD	Multi-Function Display
NTSB	National Transportation Safety Board
SKE	Station Keeping Equipment
TEMM	Threat and Error Management Model
TM	Technical Memorandum
USAF	United States Air Force
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

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